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Efficient Oxyhydrogen Mixture Determination in Gas Detonation Forming

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Abstract**—**Oxyhydrogen is a mixture of Hydrogen (H_2) and Oxygen (O_2) gases. Detonative mixtures of oxyhydrogens with various combinations of these two gases were used in Gas Detonation Forming (GDF) to form sheets of mild steel. In die forming experiments, three types of conical dies with apex angles of 60, 90 and 120 degrees were used. Pressure of mixtures inside the chamber before detonation was varied from 3 Bar to 5 Bar to investigate the effect of pre-detonation pressure in the forming process. On each conical die, several experiments with different percentages of Hydrogen were carried out to determine the optimum gaseous mixture. According to our results the best forming process occurred when approximately 50-70%. Hydrogen was employed in the mixture. Furthermore, the experimental results were compared to the ones from FEM analysis. The FEM simulation results of thickness strain, hoop strain, thickness variation and deformed geometry are promising.

Keywords**—**Sheet metal forming, Gas detonation, FEM, Oxyhydrogen.

I. INTRODUCTION

UTILIZATION of explosive materials has been well known for many applications such as sheet metal forming and welding [1]-[4]. A specialized method within the forming processes works with detonative mixtures of gases like Oxygen (O_2) and Hydrogen (H_2). Deforming sheet of metal by Gas Detonation Forming (GDF) is a dynamic manufacturing process using pressure energy produced instantaneously by the shock wave resulting from a detonation inside a combustion chamber [5]. Impulsive loads are utilized in the deformation of circular blanks and this process takes place in a few milliseconds. The pressure strength of the detonation is controlled by the amount as well as the percentage of each gas inside the chamber. The advantages of using gaseous medium are the possible automation due to an easy filling and a clean combustion. Also, both the ultimate pressure level and the duration of the ultimate pressure (pulse of pressure) can be adjusted independently to each other. Furthermore, this process can be automated for doing large number of experiments [5], [6].

The GDF process simulation based on a finite element method is used to investigate the deformation mechanisms and examine the effect of detonation pressure on the work piece [7]. The FE computations are based on three-dimensional explicit dynamics formulations [8]. The strain rate effects are incorporated using Johnson-Cook material model [9].

In this paper results of experimental tests obtained from GDF apparatus are presented. The experimental tests reported in this paper are divided into two groups: Die forming of clamped circular mild steel sheets; and efficient combination determination by varying the percentage of Hydrogen in the mixture. Also, the effect of the primary variables including pre-detonation pressure of oxyhydrogen mixture inside the chamber, the effect of die angles, and percentage of Hydrogen in mixture, on the amount of deformation and strain distribution are discussed. Furthermore, a FEM model is used to simulate this process and obtained numerical results are compared with the experimental data.

II. PROCESS PRINCIPLE

Sheet metal forming by means of gas detonation consists of placing a previously inscribed and measured blank on a conical die, evacuating the space beneath it and detonating the oxyhydrogen mixture in a closed chamber by an ignition system. A detonation consists of a shock wave and a reaction zone that is tightly coupled [10]. An ideal detonation travels at a nearly constant speed close to the theoretical or Chapman–Jouguet (CJ) velocity (Vcj); which is between 1500 and 3000 m/s in gases depending on the fuel–oxidizer combination. The reaction zone in a detonation is usually very thin, less than 10 mm for most stoichiometric fuel–air mixtures and less than 100μm for stoichiometric fuel–Oxygen mixtures. Within this reaction zone, temperature, pressure and other properties change rapidly while just downstream of the reaction zone, a much slower variation occurs due to the gas dynamics of the wave propagation process. The pressure just behind the detonation can be as high as 20–30 times the ambient pressure [11].

III. EXPERIMENTAL STUDY

A. Experimental Setup and Apparatus

Experimental tests were carried out at Guilan University's GDF apparatus. As schematically shown in Fig. 1, this apparatus consists of different parts such as ignition system, Oxygen and Hydrogen cylinder, valves for controlling the flow of gases, pressure gauges and an explosion chamber made of special seamless steel pipe with 4.5cm thickness, 53cm length and 12cm internal diameter. Also, circular sheets

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of mild steel were used as work pieces with 1mm thickness and 16cm diameter.

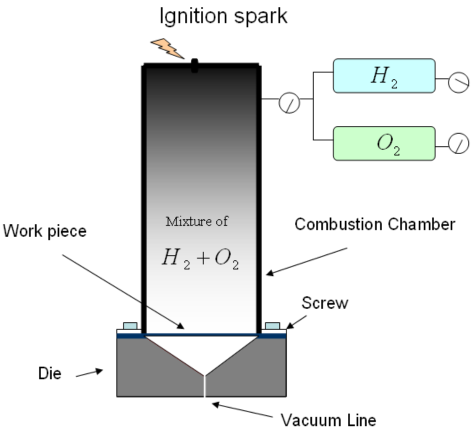

Fig. 1 A conceptual drawing of GDF apparatus

As shown in Fig. 1, the combustion chamber is filled with a mixture of oxyhydrogen. The process is started by an ignition, causing the gaseous mixture to be detonated and producing a shock wave. Being a macroscopic manifestation of an explosion, this shock wave propagates axially through the chamber at stable velocity, exceeding several times the sound velocity. Using a pre-compressed stoichiometric mixture of Oxygen and Hydrogen, the wave speed is approximately 3000 m/s, the wave thickness is less than a millimeter and the pressure directly behind it exceeds approximately 20 times the initial pressure P_0 of the gas mixture [12].

Measurement of thickness and diameter, before and after deformation at each intercept of the concentric circles with the inscribed diameter is required to determine the thickness and hoop strain distribution. Equations (1) and (2) are used to calculate the thickness and hoop strain, respectively.

$$\varepsilon_t = Ln\frac{T}{T_0} \tag{1}$$

$$\varepsilon_d = Ln\frac{D}{D_0} \tag{2}$$

where T_0, T, D_0, and D are the initial thickness, the thickness after deformation, the original diameter and the diameter of circles after deformation, respectively [13]. Mechanical properties of work pieces (sheets of mild steel) were obtained by tension tests by means of Amsler HA500. Table I shows the mechanical properties of mild steel sheets.

TABLE I
MECHANICAL PROPERTIES OF MILD STEEL BLANKS

Elastic modulus, E (GPa)	210
Poisson ratio	0.29
Density (kg/m^3)	7890
Yield Stress (MPa)	217

B. Die Forming

In die forming experiments, three types of conical dies with apex angles of 60, 90 and 120 degrees were used. Also, pre-detonation pressure varied from 3 Bar to 5 Bar. In each test, Hydrogen and Oxygen were mixed together with a specific percentage. Table II shows performed experimental tests and their condition. For simplicity, experiments with similar initial conditions were placed in the same category and all the experiments have a unique name.

TABLE II
MIXTURES' CONDITIONS OF DIFFERENT SERIES OF EXPERIMENTS

Tests' Conditions	Name	H_2(Bar) (bar)	O_2(Bar) (bar)	H_2(%)
Die angle=60, P_0=5 Bar, A series	A1	3.5	1.5	70
	A2	3	2	60
	A3	2.5	2.5	50
Die angle=90 , P_0=3 Bar, B series	B1	2.4	0.6	80
	B2	2.1	0.9	70
	B3	1.8	1.2	60
	B4	1.5	1.5	50
	B5	1.2	1.8	40
Die angle=90 , P_0=4 Bar, C series	C1	3.5	0.5	87.5
	C2	3	1	75
	C3	2.8	1.2	70
	C4	2.5	1.5	62.5
	C5	2	2	50
	C6	1.5	2.5	37.5
	C7	1	3	25
Die angle=90 , P_0=5 Bar, D series	D1	4	1	80
	D2	3.75	1.25	75
	D3	3.5	1.5	70
	D4	3	2	60
	D5	2.5	2.5	50
	D6	2.25	2.75	45
	D7	2	3	40
	D8	1.5	3.5	30
Die angle=120 , P_0=3 Bar, E series	E1	2.4	0.6	80
	E2	2.1	0.9	70
	E3	1.8	1.2	60
	E4	1.5	1.5	50
	E5	1.2	1.8	40
	E6	1	2	33
	E7	0.9	2.1	30

After the first experiment, due to the reaction between H_2 and O_2, water molecules are formed influencing the forming process and decreasing the power of the shock wave inside the chamber. Therefore, water was drained after each experiment and the combustion chamber was dried before the next test. After deformation process, the work pieces were measured again based on initial, undeformed, inscribed circles and measurements taken after deformation were compared with the initial measurements.

Figs. 2 to 11 depict results obtained from experimental tests showing thickness strain and hoop strain for each series. In order to provide representative and clear figures, some data points are removed from the hoop strain graphs. In series A (Figs. 2 and 3), the die angle is the sharpest angle among all experiments (60˚), which allows the sheets to have maximum amounts of deformation and consequently, thickness strains.

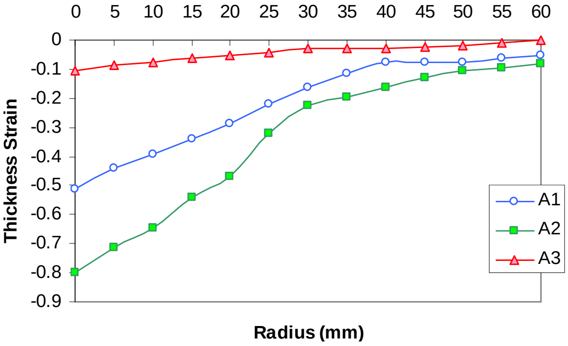

Fig. 2 Measured thickness strain for “series-A” of experiments

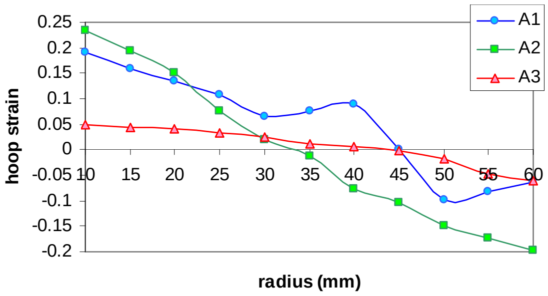

Fig. 3 Measured hoop strain for “series-A” of experiments

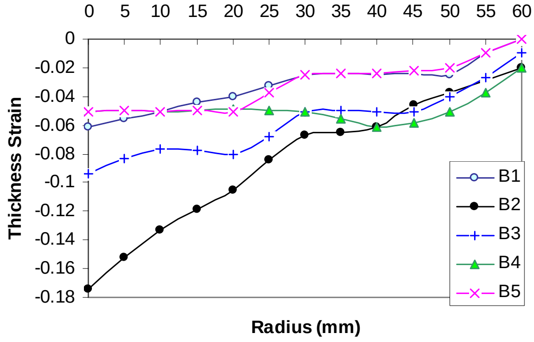

Fig. 4 Measured thickness strain for “series-B” of experiments

Figs. 4 and 5 illustrate the thickness and hoop strain variations for series B. In this series of experiments, a 90 degree conical die is used and the pre-detonation gas mixture pressure is 3 Bar. Five experiments are performed and the percentage of Hydrogen in the mixture is varied from 40 to 80%. As shown in Fig. 4, the maximum thickness strain occurs when the percentage of Hydrogen in the mixture is about 70%. Also, due to the small amount of hydrogen (40%) in the mixture in B5 test, the lowest thickness strain (-0.05) is observed in the experiment.

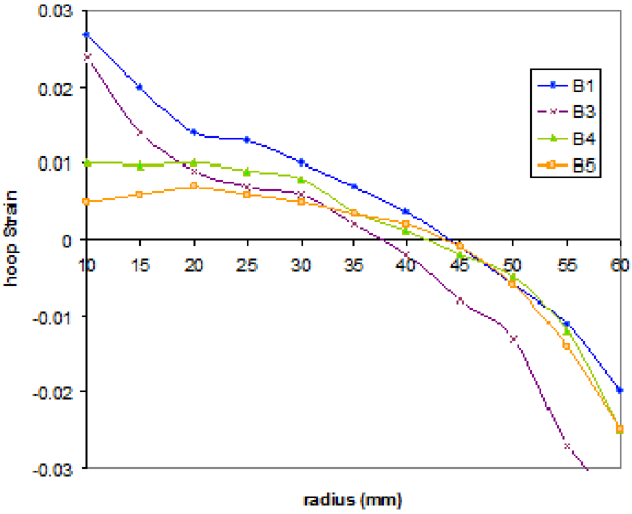

Fig. 5 Measured hoop strain for “series-B” of experiments

Figs. 6 and 7 show the strain variations for series C of experiments. Die geometry is similar to series B, while pre-detonation gas mixture pressure is increased to 4 Bar. In addition, the percentage of Hydrogen in the mixture is varied from 25% to 87.5%. Similar results are obtained in this series supporting 70 percent of Hydrogen in the mixture as the most efficient combination. Comparing results from C1 (87.5% of Hydrogen) with C7 (25% of Hydrogen), it can be observed that although percentage of Hydrogen in C1 is substantially higher than C7, the thickness strain in C1 is less than C7. This phenomenon could be interpreted by the fact that saturated mixtures have weaker detonation than others, justifying the negative effect of a high percentage of Hydrogen in the mixture on detonation power.

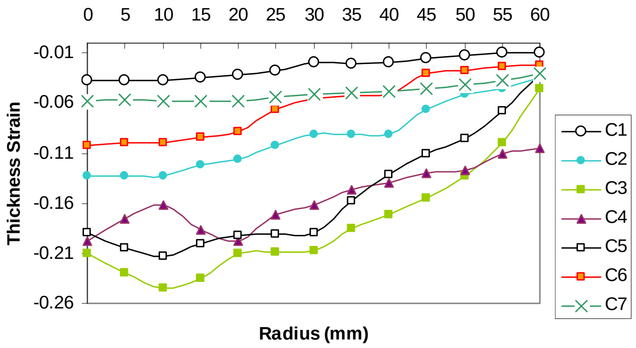

Fig. 6 Measured thickness strain for “series-C” of experiments

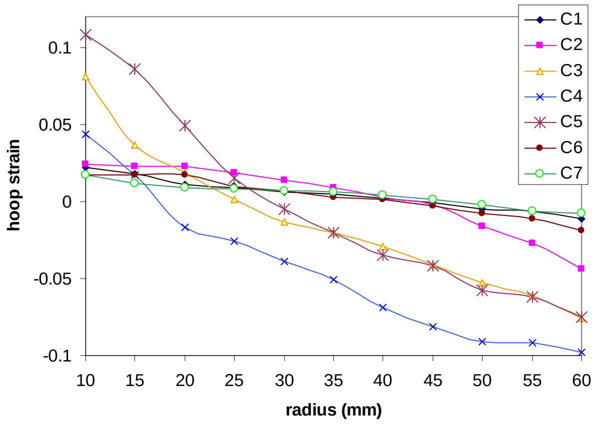

Fig. 7 Measured hoop strain for "series-C" of experiments

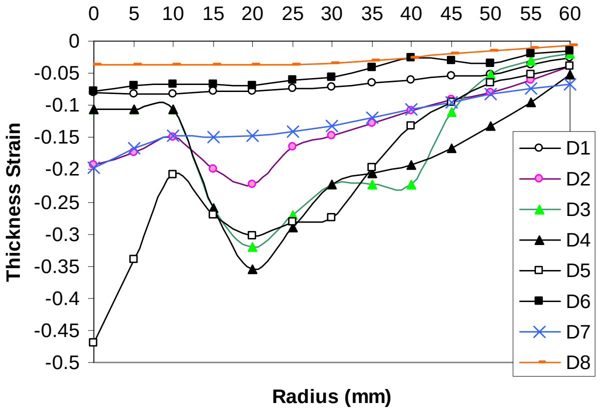

Fig. 8 Measured thickness strain for "series-D" of experiments

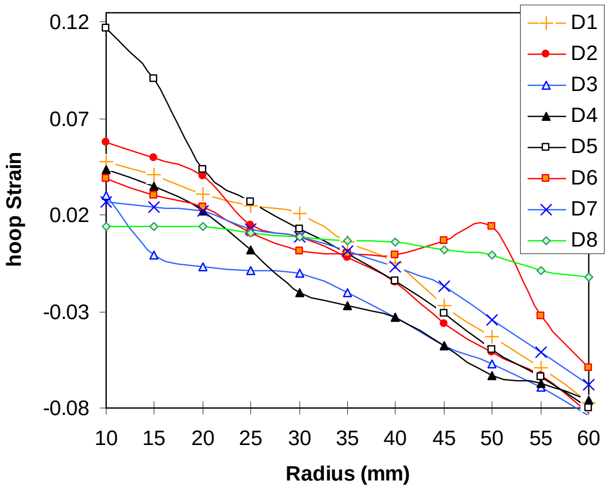

Fig. 9 Measured hoop strain for "series-D" of experiments

Figs. 8 and 9, show thickness and hoop strain measurements for series D of experiments. As mentioned in Table II, in series B, C, and D all the experiments are done on a 90 degree conical die and only the pre-detonation gas mixture pressure is varied from 3 Bar to 5 Bar. As shown in Fig. 8, an unusual behavior is observed in some experiments in this series such as D3 and D4. For instance, in D3 with 70% Hydrogen, the thickness strain is -0.1 at the center of the plate, while it decreased at the distance of 10 mm from the center and reaches to -0.33 at the radius of 20 mm before it increases gradually afterward. This behavior shows that in the area around 15 to 30 mm from the center point, the maximum reduction in thickness is experienced by the work piece and consequently, the magnitude of thickness strain is maximum.

Figs. 10 and 11 show the results for series E of experiments in which die angle is 120 degree and pre-detonation gas mixture pressure is 3 Bar and the percentage of Hydrogen in the mixture is varied from 30% to 80%. In this series of experiments similar to series D, some fluctuations in strains are observed. These variations are more obvious in tests E2 to E5 in which the percentage of Hydrogen is varied from 70% to 40%. The maximum thickness strain is occurred in the radius around 15 to 35 mm from the center point. It should be noted that in this series of experiments, E2 and E3 have the maximum reduction in thickness with 70% and 60% of Hydrogen in mixture, respectively and consequently, have the maximum magnitude of thickness strain.

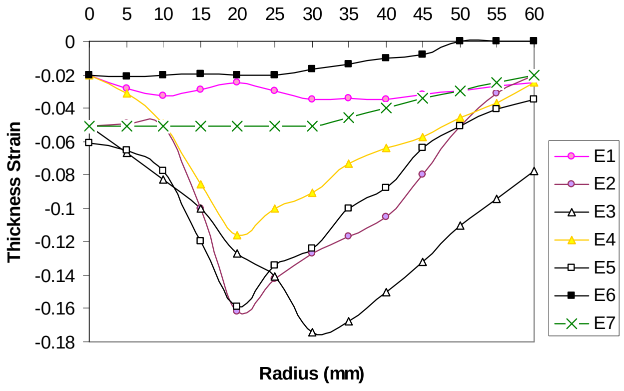

Fig. 10 Measured thickness strain for "series-E" of experiments

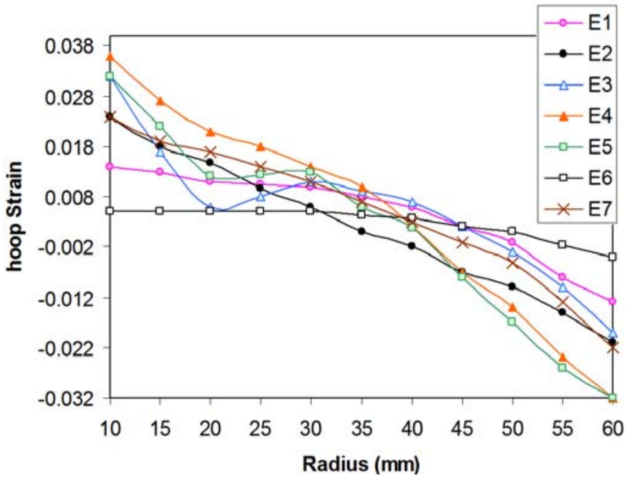

Fig. 11 Measured hoop strain for "series-E" of experiments

C. Efficient Mixture Determination

In GDF, the amount of each gas in the mixture affects the strength of traveling shock wave and thus, the forming process. As such, the percentage of Hydrogen in oxyhydrogen mixtures is one of the most influential parameters, such that varying this percentage can increase or decrease the efficiency of forming process.

To achieve an optimum gas mixture for forming process, various tests have been carried out. It should be mentioned that achieving and introducing one specific percent for all the conditions is impossible because by changing other parameters such as die geometry and pre-detonation pressure this specific percentage would be changed. Also, another item that needs to be considered is that produced parts by GDF should be obtained without any major defects such as wrinkling or rupture. The optimum detonation pressure is identified as the maximum process pressure at which the mild steel conical parts are produced free of defects.

As shown in Fig. 12, the optimum range of the percentage of Hydrogen in the mixture is determined to be between 50 to 70 percent. In the most cases, the best mixture for forming process is a mixture with 68% of Hydrogen and 32% of Oxygen, which is very close to stoicheiometry condition.

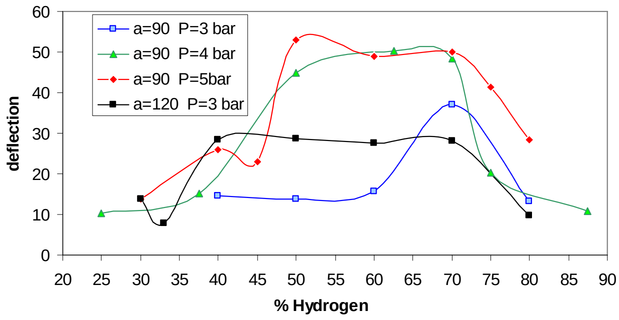

Fig. 12 Deflection of the center point of work piece at different test conditions

IV. GAS AND WAVE PRESSURE VERSUS TIME

An ideal gas has no frictional forces or bonds between its particles. The internal energy is treated as zero. The entire internal energy is then equal to the kinetic energy and thus depends only on the absolute temperature. If the internal energy is proportional to temperature, the gas in such an ideal case is referred to as polytropic gas. The entropy of this gas is a function of either temperature and volume or pressure and volume [14].

After the instantaneous explosion, the gases generally begin to expand and owing to the speed of this phenomenon, the process is adiabatic, i.e., there is no transfer of heat to the surrounding medium. The detonation wave from the explosion propagates in all direction and its front creates an impact on the surrounding medium by propagating a shock wave in it. At the same time a reflected wave expands towards the center of the source. At the center of the source, the front of the wave is contracted and the new reflected wave propagates away from the center. The procedure of creating new waves and repeating the process causes:

(1) the explosion gases decaying pulsation of reflected waves;
(2) the fading of the waves in the medium;
(3) the volume of the gases during reflection to increase until it reaches a maximum, thus making the explosive gas pressure low compared with that in the surrounding medium;
(4) an overpressure of the medium, compelling the gases and the medium to move in the opposite direction towards the center of the source;
(5) a further increase in the overpressure and a new expansion, resulting in a damped pulsation of these explosive gases [14].

V. EXPLICIT DYNAMIC SIMULATION MODEL

In GDF process, due to the fact that the problem includes multiple aspects such as mechanical, thermomechanical, and fluid-solid interaction, the numerical simulation and optimization by Finite Element Method (FEM) is not as easy as for conventional processes [12]. In the combustion chamber, the shock wave produced by gas detonation is the only agent that deforms the steel blanks and forces the material to flow into the die cavity [15]. To simulate this complex process some assumptions have to be made. The first one is to neglect the effects of thermal loading resulting from the gas detonation applying on the sheets during deformation process. In addition, the next assumption is to eliminate the gas detonation from the computational model and replace it with the measured profile of pressure inside the chamber as loading condition acting on one side of the sheets [16].

The geometry of die and blank has been modeled three times for each conical die (60, 90, and 120 degree). The die surface has been modeled as analytical rigid segments and the blank was modeled with S4R shell elements. The boundary conditions were considered as perfectly clamped as the real situations in the experiments. The strain rate effects are incorporated into the computations with the Johnson-Cook material model [9], which scales the yield stress of mild steel over a wide range of strain rate under adiabatic conditions. The material parameters for this model are given in Table III.

TABLE III

FEM CONSTANTS FOR MILD STEEL ($\dot{\varepsilon} = 1s^{-1}$)

σ_0 (MPa)	B (MPa)	n	C	Melting T (K)	m
217	234	0.643	0.076	1811	1

For all pressure histories, a total duration of 80ms is assumed and peak values of 6, 8 and 10 MPa are used for the simulations based on the assumptions validated by Kleiner [12], in which the pressure directly behind the shock wave is assumed to exceed approximately 20 times the initial pressure P0 of the gas mixture. The variation of pressure load as a function of time is shown in Fig. 13.

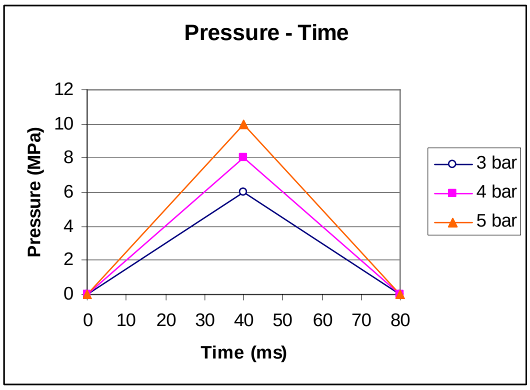

Fig. 13 Pressure-time profile incorporated in the FEM for three different initial pressures

The contact between the blank and rigid die surface is defined with the penalty stiffness method. Also, a friction coefficient of 0.2 is considered as the contact between blank and die surface.

A. Simulation Results

A 3D simulation model including the steel blank and Die cavity was constructed and the FE solution of dynamic equilibrium equations was performed using the explicit time integration method. The most similar simulation results with experimental data are observed when conical die with angle 120 degrees is used. A comparison between experimental and numerical results for E3 is shown in Fig. 14.

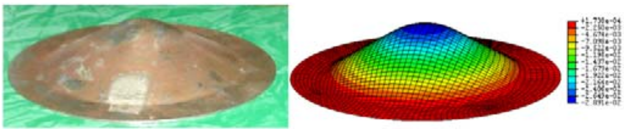

Fig. 14 Comparison of deformation for experimental and numerical results of test E3

Fig. 15 illustrates a comparison between experimental and numerical results for thickness strain for E3.

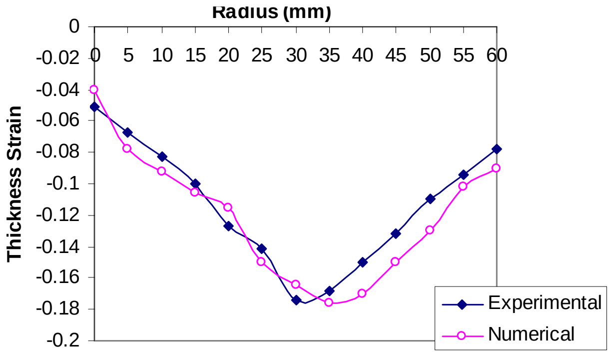

Fig. 15 Thickness strain variations for E3 experiment, experimental and numerical comparison

As shown in Fig. 16, midpoint deflection is increased by increasing the amount of impact in forming process. Also as shown in Fig. 17, a good similarity between numerical and experimental results for midpoint deflection is achieved for E3.

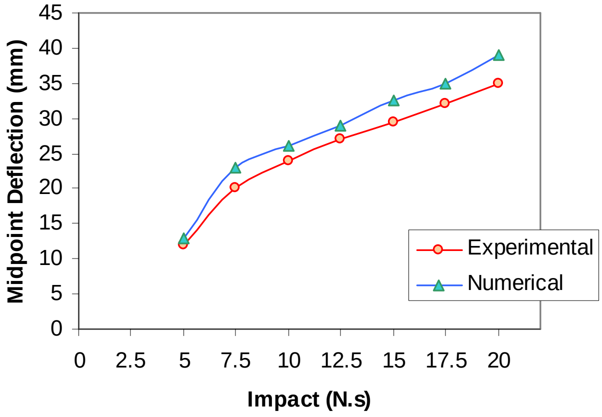

Fig. 16 Effect of impact on midpoint deflection, experimental and numerical comparison

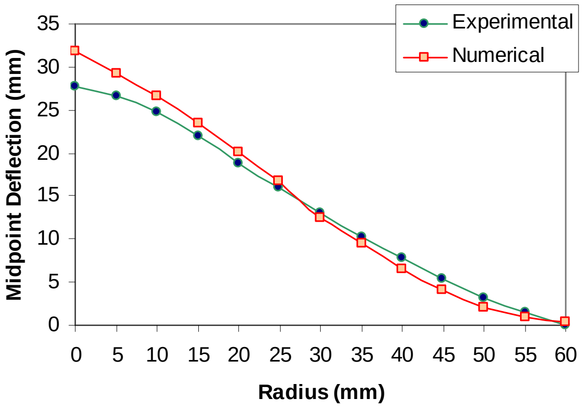

Fig. 17 Midpoint deflection for E3 experiment, experimental and numerical comparison

The effect of Hydrogen concentration in forming process for series E is shown in Fig. 18. Although in most of the experiments, the best forming results have been obtained by stoicheiometry mixtures of 68 to 70 percent of Hydrogen, as shown in Fig. 18 for series E, the best forming tests have been obtained when Hydrogen concentration in mixture was in a range between 40-70%.

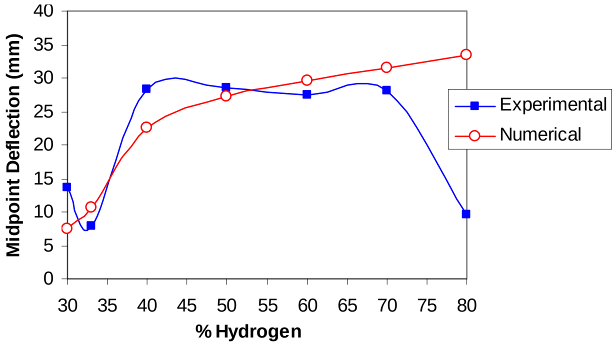

Fig. 18 Effect of Hydrogen percentage in the mixture on midpointdeflection, experimental and numerical results

VI. CONCLUSIONS

Several experimental tests for steel plates forming by means of detonating oxyhydrogen mixtures have been carried out and feasibility of this method as a forming process was validated. Also, complementary comparisons for experimental and numerical results were performed and good compatibility of the results was observed. Due to maximum height in 60 degree die (series A), the maximum amount of thickness strain and hoop strain occurred in this series of experiments. In the hoop strain measurements, at some area of the plate where the length of elements suffers no variations during deformation process, the hoop strain of these segments are zero. Importantly, the percentage of Hydrogen in the mixture and its role on the forming process was studied and a mixing 68% H_2 and 32% O_2 was found to have the best characteristics. It should be mentioned that this mixing percentage is very close to stoicheiometry condition. Furthermore, combustion and detonation of gas mixture produces some water as well as sparing smoke which dampen internal surface of detonation chamber. This moisture effects on gas mixture in the following experiments and reduces the power of detonation. Further investigations should focus on the identification of process limits for different alloys; the use of other gas mixtures as detonative gas and developing of a detonation tube with a especial geometry to increase gas mixture turbulence to achieve higher detonation power.

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